

# Modeling Spatial Risk of Diarrheal Disease Associated with Household Proximity to Untreated Wastewater Used for Irrigation in the Mezquital Valley, Mexico

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**BACKGROUND:** Reusing wastewater for irrigation is a longstanding practice that enhances crop yields and improves climate resilience. Without treatment, however, wastewater contains harmful pathogens and chemicals. Reuse of untreated wastewater has been shown to be harmful to the health of nearby communities, but the routes of exposure are unknown and do not appear to be occupational. Some routes occur throughout entire communities, such as food contamination. Other routes may be spatially dependent, such as spread by domestic animals or through aerosolization.

**OBJECTIVES:** To examine whether those wastewater exposure routes with a spatial dependency affect health, we estimated the risks of diarrheal disease in children under age 5 associated with living near wastewater canals, while adjusting for potential individual- and household-level confounders.

**METHODS:** We conducted three surveys over 1 y in the Mezquital Valley, Mexico, to measure diarrhea in children. The distance between each participating household and a wastewater canal was measured using GPS coordinates. The association between proximity and diarrhea was estimated with a multilevel logistic regression model accounting for spatial autocorrelation.

**RESULTS:** A total of 564 households completed one to three surveys, resulting in 1,856 survey observations of 646 children. Children living 100 m from a canal had 45% lower odds of diarrhea than those living within 10 m of a canal, and children living 1000 m away had 70% lower odds of diarrhea [100 m vs. 10 m adjusted odds ratio (OR) = 0.55, 95% credible interval (CI): 0.33, 0.91; 1000 m vs. 10 m adjusted OR = 0.30, 95% CI: 0.11, 0.82].

**DISCUSSION:** The estimated decline in diarrheal prevalence with household distance from a canal persisted after controlling for occupational exposure. Identifying the specific routes of exposure that drive this relationship will help identify which interventions, such as upstream treatment, can reduce health risks for entire communities where wastewater exposure occurs. <https://doi.org/10.1289/EHP6443>

## Introduction

The reuse of wastewater for agricultural irrigation has long provided farmers with a cheap, nutrient-rich, and dependable water source that amplifies crop yields. As climate change escalates water scarcity worldwide, wastewater reuse can help strengthen climate resiliency among farmers and improve the sustainability of global food systems. However, these benefits occur alongside considerable health risks to farmers, their families, and communities exposed to wastewater through reuse. Wastewater may be heavily contaminated with enteric pathogens from human and animal feces, antibiotic-resistant bacteria, and, especially in urban wastewater, toxic or biologically disruptive chemicals and metals. Treatment before reuse can reduce contamination significantly, but most generated wastewater stays untreated, particularly in low- and middle-income countries (Sato et al. 2013; Malik et al. 2015).

Associations between wastewater reuse and adverse health outcomes have been documented in numerous studies (Blumenthal et al. 2000; Contreras et al. 2017; Dickin et al. 2016). Wastewater exposure has been consistently associated with enteric infections and diarrheal disease in children (Cifuentes et al. 2000; Ensink et al. 2006; Gumbo et al. 2010; Contreras et al. 2017); however, little information exists on the most important routes of exposure

underlying these associations. Many studies have hypothesized that farmers who irrigate with wastewater are at the highest risk of infection (Dickin et al. 2016). However, three studies in Vietnam found that engaging in wastewater irrigation was not associated with diarrheal disease, potentially due to protective measures employed by farmers (Pham Duc et al. 2011, 2013, 2014). In addition, two studies in Pakistan and our previous study in Mexico found that farmers who engaged in wastewater irrigation and their families do not face higher risk of diarrhea or enteric infection when compared with nonfarming families within the same communities, whereas the entire community is at higher risk compared with other populations (Ensink et al. 2005, 2006; Contreras et al. 2017). These results suggest that the association between wastewater reuse and poor health cannot be explained by direct exposure and that unidentified indirect routes might be largely responsible for increased disease risk. These routes may include consumption of crops grown with wastewater, contact with domestic animals that interact with wastewater, flooding of land near canals, spread of fecal matter from canals by flies, and aerosolization of pathogens from wastewater (Dickin et al. 2016; Baker et al. 2018; Brooks et al. 2004, 2005; Courault et al. 2017; Hamilton et al. 2006; Julian 2016; Kowalski et al. 2017; Rosenberg Goldstein et al. 2014; Zambrano et al. 2014).

We hypothesize that the relative importance of some indirect routes of exposure, such as aerosolization of pathogens or spread by flies and domestic animals, is related to a household's physical location within a reuse system. Households that are closer to wastewater canals have more exposure to the routes described above, and thus children living in these households are more likely to have enteric infections and resultant episodes of diarrheal disease in comparison with children in farther households. To test this hypothesis, and to better understand how communities are affected by wastewater reuse, we conducted a spatial analysis on diarrheal disease among children and its association with household proximity to wastewater canals in the Mezquital Valley, Mexico.

The Mezquital Valley is an agricultural area in the state of Hidalgo that receives most of the wastewater generated by Mexico

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City through two large underground tunnels. The wastewater is then transported throughout the Valley for use in agricultural irrigation via a system of aboveground, uncovered canals (Figure 1). This reuse system has operated since 1896 and currently irrigates ~900 square miles of cropland, making it the largest and one of the oldest such systems in the world (Angelakis et al. 2018). By law, crops grown using wastewater irrigation are to be used only for animal fodder and are not for human consumption. However, we have learned through informal interviews with local farmers that crops grown with wastewater are consumed by humans through traditional food systems, local markets, and directly by farmers and their families. The Mezquital Valley was the site of previous studies that found associations between wastewater reuse and diarrheal disease and that influenced the development of the most recent update to the World Health Organization's (WHO) Guidelines for the Safe Use of Wastewater, Excreta, and Greywater (Cifuentes et al. 1998, 2000; Contreras 2017; WHO 2006). The first large-scale wastewater treatment plant for the reuse system was completed in 2018 and has the capacity to treat about half of the incoming wastewater. However, the impact of the treatment plant on irrigation water quality and health is still unknown.

In 2016, we began a longitudinal study to assess changes in disease risk associated with the eventual operation of the new treatment plant. Here, we present a Bayesian spatial analysis using household survey data and global positioning system (GPS) location data for households and wastewater canals in the Mezquital Valley. We aimed to estimate the association between diarrheal disease in children and household proximity to wastewater canals to better understand how wastewater reuse affects community health.

## Methods

### Data Source

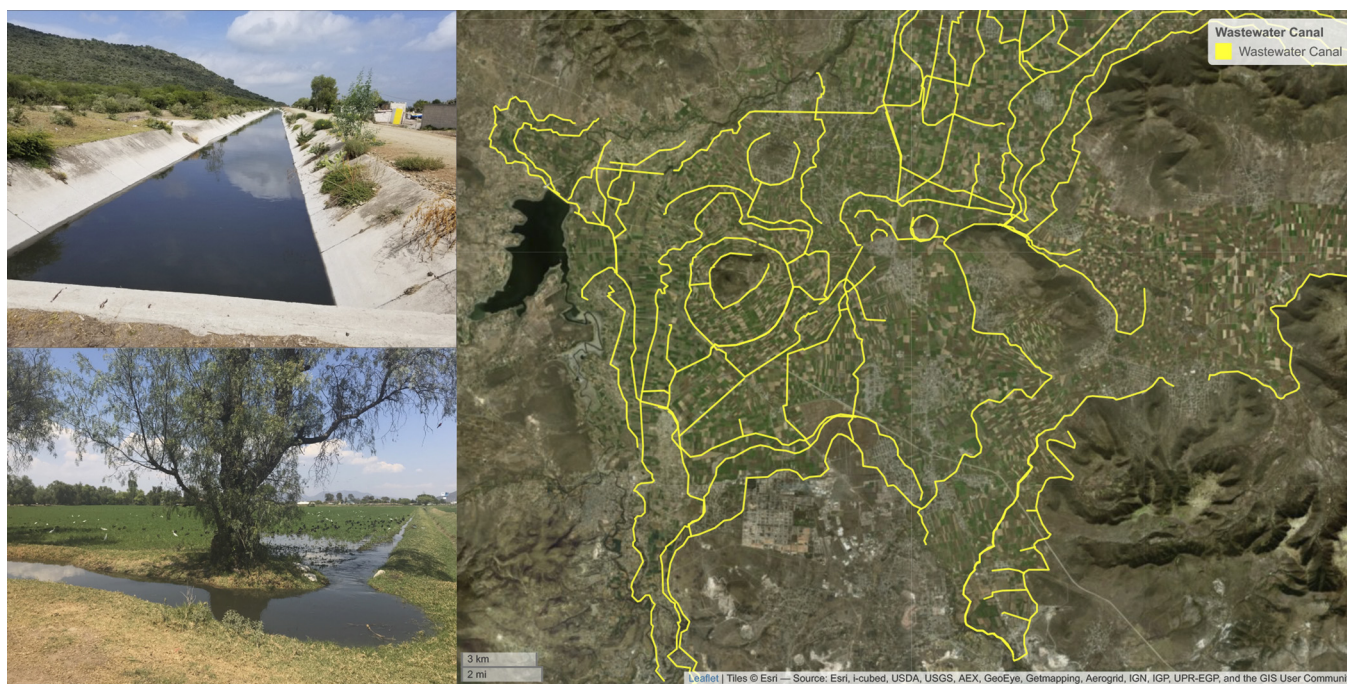
We conducted three rounds of surveys in the Mezquital Valley between November 2016 and November 2017 to longitudinally

measure diarrheal prevalence in children. Participants were recruited and surveyed during in-home visits by trained interviewers. Households were sampled from four municipalities in the Mezquital Valley that are characterized by high levels of agricultural activity and wastewater reuse: Tula de Allende, Atitalaquía, Tetepango, and Tlahuelilpan. We sampled specific localities (towns) within those four municipalities that were known to have substantial agricultural activity based on our previous work in the area (Contreras et al. 2017). A large reservoir is located between one study locality and the wastewater canal system. Because participants in this locality do not face the same exposure to wastewater canals, they were excluded from this study before analysis. The remaining localities varied by degree of rurality, including peri-urban communities around the larger city of Tula as well as more rural communities, but each locality was located near wastewater canals and engaged in agricultural activity.

Eligible households were those with at least one child younger than 4 y old in which a parent or legal guardian was present. We used the criterion of 4 y to ensure that children could be followed for 1 y while still under age 5, which is the age of interest for the diarrheal disease outcome, but respondents were asked to report on all children under 5 y old in the household. At the baseline visit, a parent or legal guardian in participating households completed a survey with questions related to sociodemographics, agricultural activities, household characteristics, hygiene practices, caregiving practices, and diarrhea in children. Follow-up surveys included questions that may change over time, including select sociodemographics and diarrhea. Diarrheal disease was recorded for children under 5 y old and defined as passing three or more loose stools in a day within the past 7 d (WHO 2017). Survey data were recorded on cellphones using the Qualtrics offline application (version 2019; Qualtrics LLC).

### Spatial Data

At the baseline visit, interviewers logged the coordinates of each household with a handheld GPS recorder. For consistency, interviewers logged coordinates while standing as close to the front



**Figure 1.** The Mexico City–Mezquital Valley wastewater reuse system: (top left) large, concrete protected segment of canal bringing wastewater from Mexico City; (bottom left) flood irrigation of cropland using temporary dug canals; (right) overview of wastewater canals throughout the Mezquital Valley. Photographs published with permission from Leon Espira at the University of Michigan.

door of the household as possible. Geographic Information Systems (GIS) shapefiles for the Mezquital Valley wastewater canal system were provided by the Instituto Nacional de Estadística y Geografía (INEGI) of Mexico. These files describe the entire canal system around these study communities but exclude the smallest canals that bring water directly to fields. These excluded canals could be a missed source of exposure to households, but they are generally used only during irrigation periods and do not contain water at other times. The shortest distance between each household and any point along a wastewater canal was calculated in meters using ArcMaps (version 10.6) and serves as the primary exposure variable (ArcGIS). This exposure variable did not consider how many canals were near a household. If households were equally close to more than one canal segment, the exposure variable remained a single value for the closest point to any canal.

### Spatial Analysis

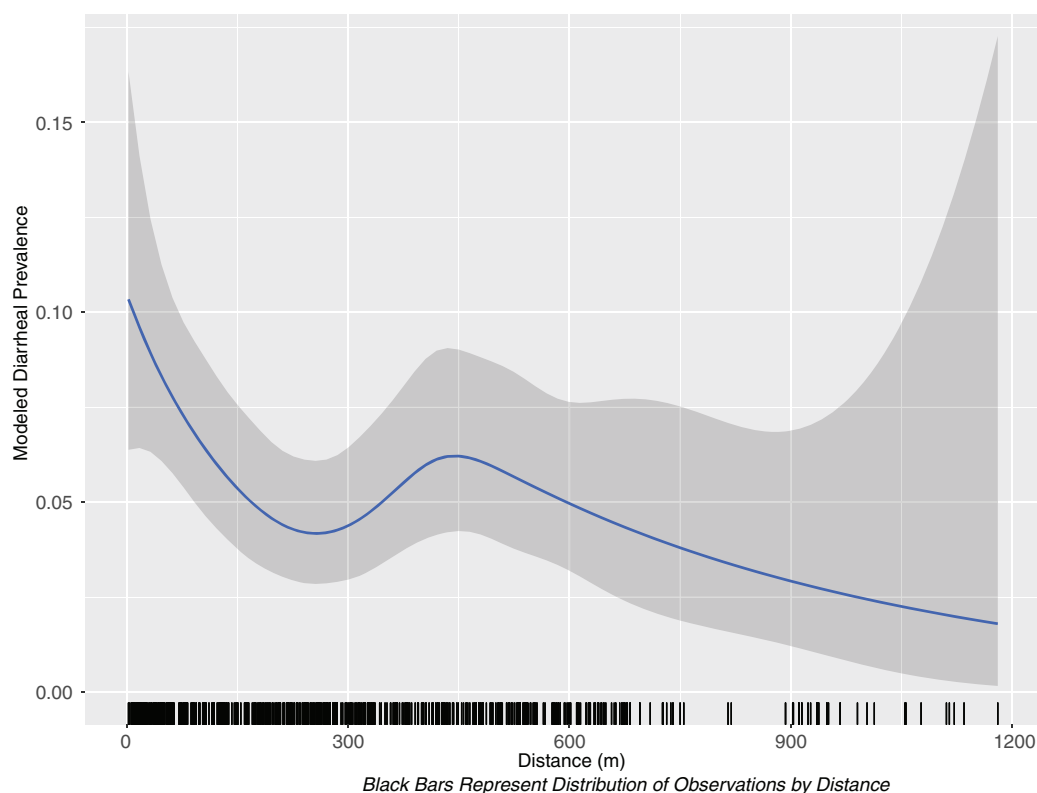
The outcome for our analysis, diarrheal disease within the previous 7 d, was recorded for each child under age 5 in participating households at each survey round. The primary exposure, household distance to a canal, was treated as continuous in meters. For descriptive analyses, the prevalence of the outcome and proportions or mean values of potential covariates were calculated across quintiles of household distance. In addition, we applied a smoothing function to the prevalence of diarrhea over household distance among all observations to visualize the unadjusted relationship between diarrheal prevalence and distance (Figure 2). This analysis indicated that the relationship between distance from a canal and diarrheal prevalence was nonlinear, with a sharp decline in prevalence over the first 250 m. The rate of decay slowed significantly after this point.

The exponential decrease in crude diarrheal prevalence with increasing distance suggests that changes in exposure to wastewater

occurring nearest to canals are more important than changes at farther distances. This implication matches theories of pathogen transport through aerosolization, one proposed spatial route of exposure. Aerosolized pathogens are dispersed through the wind and die off or settle over distances. Pathogen die-off and dispersal of aerosols are generally modeled with exponential functions (Courault et al. 2017; Brown and Mohr 2016). We assume that risks from other spatial routes of exposure, such as contact with contaminated animals, follow a similar decay. To capture this relationship, we modeled the natural log of distance between a household and a canal as the primary exposure variable. This transformation of distance treats relative increases in distance as more important for diarrhea than absolute increases. For example, the expected difference in risk between 10 and 100 m is greater than the expected difference between 100 and 190 m.

We fit hierarchical logistic regression models via Markov chain Monte Carlo (MCMC) using RStan (version 2.19.2; Stan Development Team). We estimated the change in odds associated with a single meter increase in household distance from a canal and used that model coefficient to estimate the change in odds associated with a 10-fold and a 100-fold increase in distance. Random intercepts specific to each locality (town) were introduced to control for residual correlation in diarrheal prevalence within communities that is independent of the effects of distance to a canal. Due to the small number of households from certain communities, some spatially contiguous localities were combined into a single unit, resulting in nine locality groups. Random intercepts for each household also were included to account for repeated observations of households through multiple survey rounds.

Households that are close to each other, and thus share a similar distance exposure, also could share similar characteristics or exposures that are related to disease status. To account for that possibility, we included a spatial autocorrelation model that considered



**Figure 2.** Relationship between diarrheal disease and distance between a household and the closest point on a wastewater canal: diarrheal prevalence (blue line) and 95% confidence intervals (gray area) were estimated with an unadjusted smoothing function using all 1,856 observations; black bars along the x-axis display the distance locations of all observations.

potential spatial clustering of diarrheal disease risk unrelated to canal exposure. Specifically, we estimated the household random intercepts using a Gaussian process (GP) prior, specific to each locality group, which considered covariance with nearby households. The GP was parameterized with a Matérn covariance function that had a smoothness parameter fixed to 3/2, with the ratio of the length-scale (rate at which household correlation decays with distance) and signal amplitude learned from the data (Stein 1999; Banerjee et al. 2014). To ensure that the spatially structured random effect specifically captured clustering of risk between nearby households, the household GP was constrained using an informative prior for the length-scale parameter that favored a spatial correlation of 0.5 at a distance of 60 m, declining to nearly zero at 400 m (Banerjee et al. 2014). Nevertheless, inferences were robust to changes to the prior selected for length-scale (Table S1). Final models were run with eight chains of 4,000 iterations each, and convergence was assessed using the Gelman-Rubin statistic (Gelman and Rubin 1992).

### Covariate Selection

Model covariates were potential confounders of the relationship between household distance from a canal and diarrheal disease [socioeconomic status (SES) and access to sewerage], a predictor of diarrheal disease that is not related to distance but may increase precision (ages of children), and study factors to control for potential heterogeneity between surveys (survey round and season). We selected these covariates based on prior knowledge of their causal relationships with diarrheal disease and our understanding of their possible association with household proximity to wastewater canals in the Mezquital Valley. After assessing the relationship between each covariate and the primary outcome and exposure variables through bivariate descriptive analyses, we decided to include each variable as covariates in our final model.

SES factors included caregiver education level in total years completed, a binary indicator of occupation in agricultural or pastoral fieldwork, and an overall wealth indicator comprising seven household ownership questions (presence of a refrigerator, cellular telephone, vehicle, washing machine, microwave, computer, and flat-screen television). Households were asked about three

additional assets. Those three assets were not included in our analysis because they were owned by almost all households in the study (electricity and any television) or by almost no households (Internet access in the household). The remaining seven ownership questions were used to construct a wealth index using principal component analysis (PCA) (Abdi and Williams 2010). The calculated principal components (PCs) did not account for much variation in the questions, resulting in a wealth index that was highly correlated with the sum of the seven binary ownership variables (correlation coefficient = 0.99). Tertiles of the wealth index were calculated and used in adjusted models. Households that reported a connection to the public sewage network or to a private septic tank were considered to have access to sewerage. This operationalization assumes that private septic tanks protect household members from fecal exposure to a degree similar to that of the public system, although we did not confirm that the septic tanks in our study were safely constructed and emptied to protect health. The age of each child was calculated in months using the date of survey completion. After descriptive analyses indicated a nonlinear association between age and diarrhea, age was modeled using a categorical variable with eight age groups (0–9, 10–15, 16–21, 22–27, 28–33, 34–39, 40–45, and 45–59 months). The rainy season was defined as May through October based on statewide rainfall data from the National Meteorological Service of Mexico for the years from 2004 to 2017. However, each round took place fully in either the rainy or dry seasons, resulting in complete collinearity of the two variables. The baseline survey took place during the dry season, and the first and second follow-up surveys took place during the rainy season. We included study round in adjusted models, which accounts for any potential differences between the rainy and dry season but precludes estimation of an independent effect of season.

### Attributable Risk

After estimating the adjusted association between household distance from a canal and diarrheal disease, we next estimated the proportion of risk at each household location that was attributable to canal proximity. The attributable risk proportion was defined as the proportion of risk that would be prevented if a household

**Table 1.** Characteristics of study households and children by quintile of household distance to a wastewater canal.

	Quintile 1 (n = 113)	Quintile 2 (n = 113)	Quintile 3 (n = 112)	Quintile 4 (n = 113)	Quintile 5 (n = 113)	Total (n = 564)
<b>Household characteristics</b>						
Distance to a canal in meters [mean (Range)]	41 (2–82)	150 (82–219)	276 (219–345)	447 (350–533)	717 (537–1,181)	Overall Mean: 327
Total years of caregiver education (mean ± SD)	9.3 ± 3.2	9.5 ± 2.5	9.8 ± 2.9	9.0 ± 3.1	9.9 ± 3.0	9.5 ± 3.0
Has refrigerator [No. (%)]	94 (83)	88 (78)	88 (79)	88 (78)	89 (79)	447 (79)
Has cellular telephone [No. (%)]	108 (96)	103 (91)	103 (92)	109 (96)	104 (92)	527 (93)
Has vehicle [No. (%)]	47 (42)	36 (32)	43 (38)	43 (38)	36 (32)	205 (36)
Has washing machine [No. (%)]	71 (63)	60 (53)	57 (51)	61 (54)	74 (65)	323 (57)
Has microwave [No. (%)]	31 (27)	24 (21)	26 (23)	17 (15)	29 (26)	127 (23)
Has computer [No. (%)]	18 (16)	6 (5)	12 (11)	6 (5)	19 (17)	61 (11)
Has flat screen television [No. (%)]	68 (60)	71 (63)	63 (56)	60 (53)	74 (65)	336 (60)
Has field worker [No. (%)]	21 (19)	35 (31)	45 (40)	39 (35)	28 (25)	168 (30)
Owns dog [No. (%)]	81 (72)	80 (71)	84 (75)	71 (63)	78 (69)	394 (70)
Has access to sewerage [No. (%)]	90 (80)	110 (97)	110 (98)	109 (96)	109 (96)	528 (94)
Had more than one child under five during at least one survey round [No. (%)]	6 (5)	21 (19)	17 (15)	15 (13)	20 (18)	79 (14)
Had diarrheal case at any survey round [No. (%)]	28 (25)	19 (17)	12 (11)	22 (19)	16 (14)	97 (17)
<b>Characteristics of all child observations (n = 1,856)</b>						
Child had diarrhea in preceding week [No. (%)]	31 (8)	20 (5)	12 (3)	26 (7)	16 (4)	105 (6)
Age of child in months (mean ± SD)	27.7 ± 13.7	27.2 ± 14.5	28.4 ± 13.9	27.3 ± 13.7	26.9 ± 14.3	27.5 ± 14.0

were minimally exposed to a wastewater canal (Suzuki et al. 2012). Minimal exposure was defined as the exposure faced at the distance of the farthest household within each locality group. We estimated the attributable risk proportion by comparing the modeled prevalence at the observed distance of a household with an estimated prevalence as though the household were at the minimal-exposure distance in its locality group, holding all else constant. The attributable risk proportion (ARP) was calculated for each household as:

ARP =

$$\frac{\text{Risk at Observed Distance} - \text{Risk at Counterfactual Distance}}{\text{Risk at Observed Distance}}$$

The population ARP was calculated as the mean ARP across households. Population ARPs were calculated using all households in the study. To understand the risks among the most intensely exposed households, we also summarized the population attributable risk for the subset of households within 100 m of a canal using the same counterfactual distances. In addition, ARPs were calculated along one canal segment to visualize an example of the spatial decay of attributable risk. We divided a map of the canal segment into a grid of 10-m by 10-m cells and computed the attributable risk for each cell in the grid. The counterfactual maximum distance used for calculation was the maximum distance to the canal across all grid points, which was 415 m.

Results

Household Characteristics

A total of 568 households completed the baseline survey. Of those, 550 (97%) completed the first follow-up, and 546 (96%) completed the second follow-up survey. Four households were excluded due to missing covariates, resulting in 1,664 total interviews for analysis. Seventy-nine of these households had more than one child under age 5 during at least one survey round. A total of 646 children were observed at one or more survey rounds, resulting in a total of 1,856 child observations. Furthermore, 596 (92%) of those children were recorded in all three rounds, 18 (3%) were recorded at two rounds, and 32 (5%) were recorded at only one round, including children born between rounds. The average distance from a household to a wastewater canal was 327 m (range: 2 m–1,181 m). There were no clear trends across distance quintiles for any wealth indicator variable measured (Table 1). The quintile of households closest to a canal had the lowest proportion of households engaged in fieldwork (19%) and with access to sewerage (80%). The same quintile had the highest proportion of households that reported diarrheal disease at least once during the study (25%).

A total of 105 children were reported to have diarrhea during any survey round (6%). These included 46 cases (7% of 633 children measured in the baseline survey) at baseline, 37 (6% of 608 children) during the first follow-up, and 22 (4% of 615 children) during the second follow-up. Households that reported at least one case were less likely to include a field worker (19% vs. 32%) and were more likely to have a vehicle, a microwave, and a computer (Table 2). Children with diarrhea were younger than noncases (21.4 vs. 27.9 months old) and fewer children had diarrhea during the rainy season compared with during the dry season (56% vs. 44%; Table 3). The average distance from a canal was shorter for households that reported a case of diarrhea during any survey compared with those that never reported a case (mean = 278 vs. 337 m). SES indicators, household

Table 2. Characteristics of study households that reported diarrhea at least once during any round and households that never reported diarrhea.

	Reported diarrhea at least once at any round (n = 97)	Never reported diarrhea (n = 467)	Total (n = 564)
Distance to a canal in meters (mean ± SD)	278 ± 236	337 ± 255	327 ± 253
Total years of caregiver education (mean ± SD)	9.4 ± 3.2	9.5 ± 2.9	9.5 ± 3.0
Has refrigerator [No. (%)]	76 (78)	371 (79)	447 (79)
Has cellular telephone [No. (%)]	93 (96)	434 (93)	527 (93)
Has vehicle [No. (%)]	37 (38)	168 (36)	205 (36)
Has washing machine [No. (%)]	57 (59)	266 (57)	323 (57)
Has microwave [No. (%)]	27 (28)	100 (21)	127 (23)
Has computer [No. (%)]	16 (16)	45 (10)	61 (11)
Has flat screen television [No. (%)]	59 (61)	277 (59)	336 (60)
Has field worker [No. (%)]	18 (19)	150 (32)	168 (30)
Owens dog [No. (%)]	61 (63)	333 (71)	394 (70)
Has access to sewerage [No. (%)]	88 (91)	440 (94)	528 (94)
Had more than one child under five during at least one survey round [No. (%)]	17 (18)	62 (13)	79 (14)

distance, and diarrheal prevalence varied among locality groups as expected, given general background differences among localities (Table S2).

Spatial Analysis

After considering model covariates individually and in combination, the final model was adjusted for age of the child (using eight age groups: 0–9, 10–15, 16–21, 22–27, 28–33, 34–39, 40–45, and 45–59 months), survey round, caregiver education in total years completed, tertile of wealth based on PCA, and presence of a field worker. The adjusted posterior median odds ratio (OR) for a 10-fold increase in distance to a canal (e.g., 100 m vs. 10 m) in the adjusted model was 0.55 [95% credible interval (CI): 0.33, 0.91; Table 4]. Based on the same estimate, the OR for a 100-fold increase in distance to a canal (e.g., 1000 m vs. 10 m) was 0.30 (95% CI: 0.11, 0.82; Figure 3). The odds of diarrhea were lower among older children and those living in households with a fieldworker.

Attributable Risk

The proportion of cases of diarrheal disease in all households attributable to proximity to wastewater canals was 24% (95% CI: 5%, 38%). Of the 105 cases that occurred in our study, 25 (95% CI: 5, 40) were potentially attributable to canal exposure using this estimate. Among diarrheal cases occurring in households

Table 3. Characteristics of 1,856 survey observations of 646 children by diarrheal disease status at each observation.

	Had diarrhea (n = 105)	Did not have diarrhea (n = 1,751)	Total (n = 1,856)
Baseline survey [No. (%)]	46 (44)	587 (34)	633 (34)
First follow-up [No. (%)]	37 (35)	571 (33)	608 (33)
Second follow-up [No. (%)]	22 (21)	593 (34)	615 (33)
Rainy season [No. (%)]	59 (56)	1,164 (66)	1,223 (66)
Age of child in months (mean ± SD)	21.4 ± 11.1	27.9 ± 14.1	27.5 ± 14.0

**Table 4.** Results of Bayesian logistic models on the association between household distance to a wastewater canal and diarrheal disease in children with random intercepts for locality and spatially correlated household intercepts for repeated observations.

	Crude model OR (95% CI)	Adjusted model OR (95% CI)
10-fold increase in distance from a canal (e.g., 100 m vs. 10 m away) <sup>a</sup>	0.58 (0.36, 0.96)	0.55 (0.34, 0.91)
100-fold increase in distance from a canal (e.g., 1,000 m vs. 10 m away) <sup>a</sup>	0.34 (0.13, 0.93)	0.30 (0.11, 0.82)
Child aged 10–15 months vs. 0–9 months	—	2.20 (1.05, 4.49)
Child aged 16–21 months vs. 0–9 months	—	1.84 (0.86, 4.07)
Child aged 22–27 months vs. 0–9 months	—	1.20 (0.52, 2.83)
Child aged 28–33 months vs. 0–9 months	—	0.73 (0.28, 1.81)
Child aged 34–39 months vs. 0–9 months	—	1.15 (0.49, 2.78)
Child aged 40–45 months vs. 0–9 months	—	0.15 (0.03, 0.58)
Child aged 46–59 months vs. 0–9 months	—	0.27 (0.06, 0.94)
Middle vs. lowest tertile of wealth indicator	—	0.69 (0.38, 1.23)
Highest vs. lowest tertile of wealth indicator	—	1.03 (0.58, 1.85)
1-y increase in education completed by caregiver	—	0.97 (0.90, 1.05)
Field worker in the household vs. no field worker	—	0.52 (0.26, 0.96)
First follow-up survey vs. baseline survey	—	0.87 (0.53, 1.39)
Second follow-up survey vs. baseline survey	—	0.48 (0.27, 0.83)

Note: —, no data; CI, credible interval; OR, odds ratio.

<sup>a</sup>Both results are based on the same model estimate for a 1-m increase.

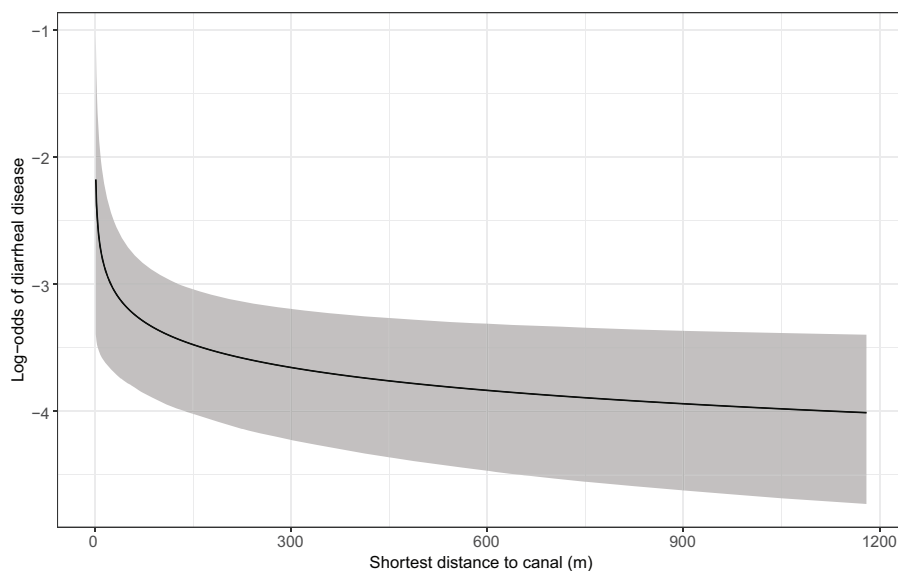
within 100 m of a canal, the population attributable risk proportion was 50% (95% CI: 11%, 71%), indicating that 16 (95% CI: 4, 23) of the 32 cases occurring in this group were potentially attributable to canal exposure. Figure 4 demonstrates the spatial decay

of attributable risk as household distance increases along an example canal segment.

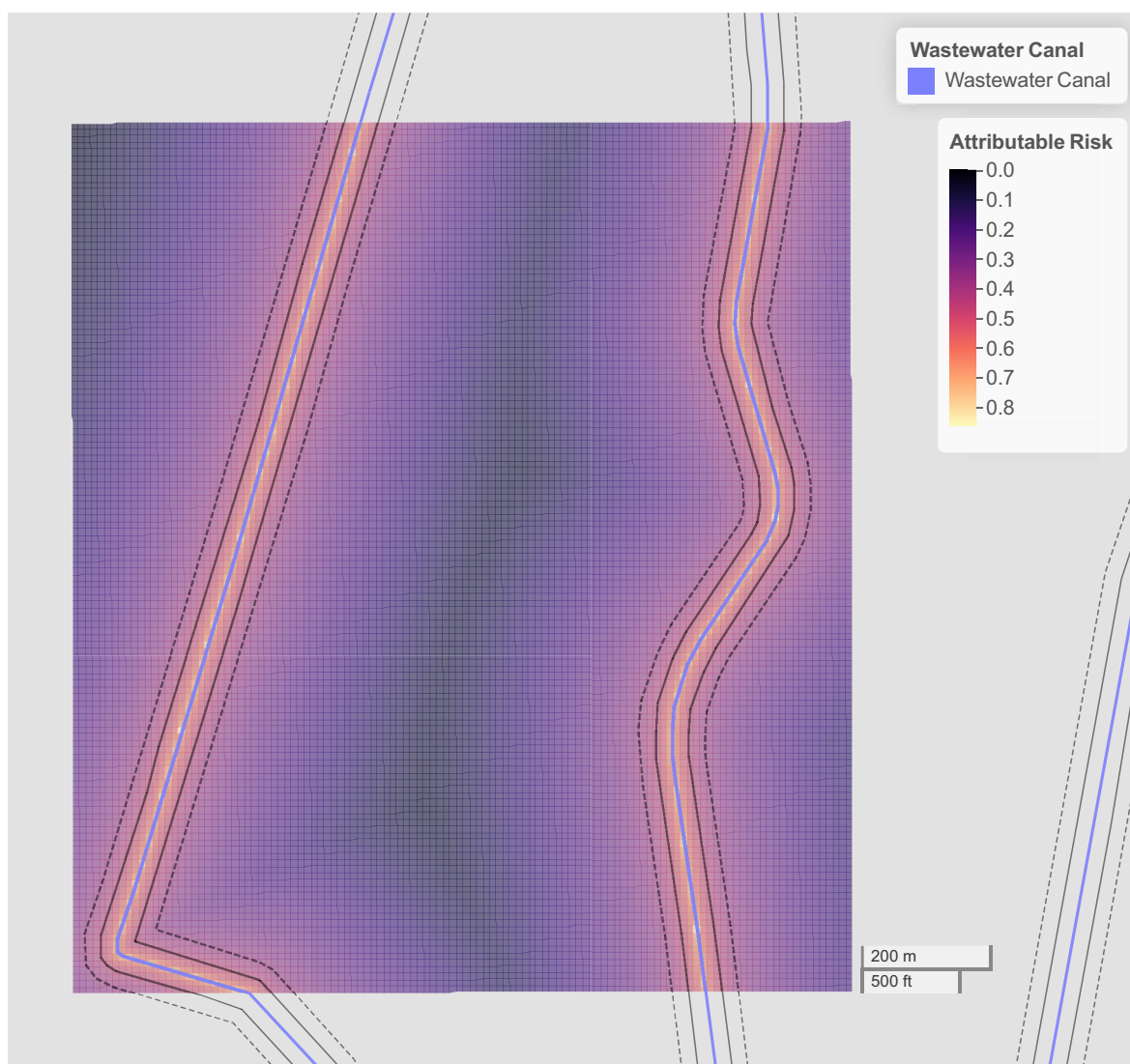
## Discussion

Wastewater reuse for irrigation across the world is an important practice that will only grow over time as a tool to alleviate water scarcity and improve climate resilience. However, to maximize the benefits of increased reuse, more attention is needed to understand its accompanying health risks. This need is especially true in low- and middle-income countries, where less than a quarter of wastewater generated is ever treated (Malik et al. 2015). The health risks of wastewater reuse should be considered along the entire reuse system, including generation and transportation of waste, agricultural practices during and after wastewater application, community-wide risks where wastewater irrigation occurs, and final consumption of crops grown with wastewater. Previous work has shown that this system as a whole is associated with increased risk of diarrheal disease in children and also that direct participation in wastewater irrigation is not a significant route of exposure for farmers' families (Contreras et al. 2017; Ensink et al. 2005, 2006; Pham Duc et al. 2011, 2013, 2014). Farmers working on fields that are irrigated with wastewater theoretically have a very high exposure and could expose their own children by carrying pathogens from the field to the home on their clothes or hands. However, we found that the odds of diarrhea actually were lower for children living in households engaged in agricultural or pastoral fieldwork compared with children in households without a fieldworker, possibly due to unmeasured socioeconomic or behavioral differences. We did not ask households to report which specific household members worked in agriculture, and these results could be different among households where agricultural workers are also primary caregivers of children. Although the reasons for their lower risk are still unknown, this result supports results of previous research findings that occupation is not the primary pathway for harmful wastewater exposure.

In this study, we focused on community-wide risks that are specifically related to household proximity to wastewater canals that transport untreated wastewater for irrigation in the Mezquital Valley, Mexico. We estimated that the risk of diarrheal disease in children under five decreased rapidly as distance between the



**Figure 3.** Posterior log-odds of diarrheal disease (black line) and 95% credible interval (gray area) over shortest distance between a household and a wastewater canal: Model covariates (child age, wealth tertile, caregiver education level, presence of a field worker, and survey round) were set to equal their average for each child.



**Figure 4.** Spatial map of model results along an example wastewater canal segment: The proportion of diarrheal disease attributable to household proximity to a wastewater canal was calculated for each location within the map, with distance bands drawn at 25 m (solid line) and 50 m (dashed line); the portion of risk attributable to distance is highest at the canal (yellow) and lowest at the midpoint between the two canals shown (dark purple); proportions were calculated for a hypothetical household with average covariate values.

household and a wastewater canal increased. Children living just 100 m away from a canal had over 45% lower odds of diarrheal disease in comparison with children in households 10 m from a canal. Children living 1,000 m away had 70% lower odds in comparison with those living 10 m away, which represents the true range of distance observed in our study. The closest 2% of households lived within 10 m of a canal, and the farthest 2% of households lived more than 1,000 m away. The average distance between a household and a wastewater canal in our sample was 327 m. Based on these model results, a household at the average distance had 59% (95% CI: 14%, 81%) lower odds of diarrhea in comparison with a household located 10 m away. We also estimated that 24% of all cases of diarrhea in our study, and 50% of cases in households within 100 m of a canal, were attributable to household proximity to a wastewater canal, based on the results of our model.

Our ability to estimate this association was aided by the collection of GPS locations for households and the availability of detailed canal maps, allowing for precise calculation of the exposure variable. Our understanding of household exposure would have been improved with more detailed spatial data on elevation,

canal flow and width, and barriers between canals and households. In addition, we did not account for households that potentially were exposed to multiple canals or households that had more cumulative exposure to a single canal. Because we were unable to assess how these factors may have reduced the true exposure, it is possible we misclassified the exposure level of close households by using a unidimensional measure in distance alone. Using a more nuanced exposure variable that considers these factors would provide a clearer understanding of the relationship between wastewater canals and health. We were able to control for potential confounding between diarrhea and household distance to a canal by SES, child's age, and season, although residual confounding could be present from unmeasured factors. The inclusion of multiple rounds of household surveys in this study also allowed us to observe temporal changes in the prevalence of diarrhea over one year, and the inclusion of spatially dependent random effects helped account for incidental similarities between neighboring households that have similar distance exposures.

Further research should build on these results to determine the more specific routes of exposure that could lead to spatially related

disease risk where wastewater is reused. Exposure to pathogens through occupation and consumption of crops occurs, but we do not believe that these exposures are related to household location and therefore would not explain the results of this study. Aerosolization of pathogens directly from wastewater canals into nearby communities is a possible route, with potential aerosolization and transport of pathogens demonstrated at spray irrigation sites (Rosenberg Goldstein et al. 2014) and wastewater treatment plants (Courault et al. 2017; Kowalski et al. 2017). Less is known about the potential for aerosolization from large, slower-moving canals. In addition, more information is needed on zoonotic transmission of pathogens between animals that interact with wastewater and humans living nearby. Based on informal discussions with local residents, people in the Mezquital Valley generally do not interact directly with wastewater canals outside of agricultural work. However, we have observed dogs, cows, sheep, and chickens swimming in and drinking wastewater directly from the canals. Flies also are common along wastewater canals. Studying pathogen spread from animals, on their bodies or in their feces, and from flies could help explain the spatial gradient of pathogen transmission and disease risk. Finally, the role of space should be investigated for other health outcomes associated with wastewater reuse, such as skin diseases and the spread of antibiotic resistant bacteria, to demonstrate the full scope of spatially related health risks.

The WHO's "Guidelines for the Safe use of Wastewater, Excreta, and Greywater" describe pathogen reduction through wastewater treatment as the primary tool to improve safety of wastewater reuse. Treatment represents the ideal form of improving health throughout the entire wastewater reuse system, because the wastewater coming into contact with farmers, crops, and nearby communities is made safer before any exposure. However, the WHO also recommends reducing pathogen exposure through agricultural practices (e.g., drip irrigation), occupational measures (e.g., protective clothing), and consumer practices (e.g., produce disinfection and cooking) (WHO 2006, Volume II, Section 5). Although these measures already could be partially responsible for historical reductions in diarrheal prevalence in the Mezquital Valley (Contreras et al. 2017), our results suggest that there are additional exposure routes related to the presence of wastewater canals that affect the entire community and would not be affected by these strategies. Wastewater treatment would be expected to reduce exposure through any of these routes. However, some communities within the Mezquital Valley still discharge sewage into the canals without treatment, potentially propagating contamination and negating some of the benefits of upstream treatment. If exposure to wastewater through the indirect routes suggested by our analysis persists despite upstream treatment, more focus on small-scale, local sewage treatment may be necessary. Other local interventions, such as covering wastewater canals or building fencing around them, could help prevent transmission from certain exposure routes; however, learning which pathways truly drive disease risk is necessary to design appropriate interventions. Finally, although these results are specific to a wastewater reuse system, their implications should be considered for many poor communities living near open sewers that carry wastewater away from urban centers across the world. Better understanding the routes of exposure between wastewater and health will help to identify which protection measures and forms of treatment would be most effective in continuing to improve the safety of wastewater management worldwide.

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